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Final Report

Evaluation of a Pneumatic Marian Soil Sampler Concept

by

John L. Schaefer, James K. Neathery and John M. Stencel
Center for Applied Energy Research
University of Kentucky
Lexington, KY 40511

for

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Final Report

Evaluation of a Pneumatic Martian Soil Sampler Concept

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BACKGROUND

In future proposed Martian explorations, rovers will be used to traverse the planet surface, performing various surface and atmospheric evaluations. It is proposed that, on one of the missions, a rover be equipped with a subsurface soil probe and a pyrolytic analyzer. The analyzer would heat the soil sample and evaluate evolved gases for organics and water. These samples would be collected in areas considered most promising for detection of existing or extinct life. Current equipment being considered for the subsurface probe revolve around modification of terrestrial auger boring equipment.

In our research, a novel subsurface sampling device which has the potential advantages of being more compact, lighter weight, containing fewer moving parts and being more dependable than mechanical augers, was tested on simulated Martian soil. The probe design is based on particle fluidization principles and, for our initiating laboratory testing, utilizes a concentric tube geometry consisting of a rigid outside casing surrounding an internal fluidizing gas delivery tube. Soil, loosened by the fluidizing gas, is transported to the surface via the annulus created by the concentric tubes.

For a pneumatic sampler to be considered a feasible alternative for subsurface Martian soil collection, several issues must be considered. First, the sampler must be able to reliably achieve required soil penetration depths. While the time to reach these depths is not considered a critical factor, reasonable boring times are desired. Second, the weight of gas used to reach full penetration should be minimized. It is assumed that the gas requirements will dictate the method of gas compression and storage on Mars, though this matter was not addressed in this research. Finally, the soil sampling system weight should be minimized. For this study, the weight of the probe (which comprised the total normal force required for soil sampling) was monitored.

EXPERIMENTAL INVESTIGATION

All penetration tests were conducted in a test column containing silica sand with properties similar to Martian soil [1]. Properties of the sand are described in the Results section of this report. Test equipment, shown in Figure 1, was assembled and used to conduct a parametric evaluation of the pneumatic soil sampler concept. A description of the experimental investigation follows.

Test Apparatus

The silica sand was confined in a 20 cm diameter plexiglass cylinder, 2.2 m in height. The filled cylinder rested on a load cell which provided data for calculating sand bulk density, probe weight, and weight of sand removed during testing. Sand compaction was achieved by using a pneumatic vibrator, attached to the side of the cylinder. A guide, designed to impose minimal resistance to probe movement yet maintain the probe in a vertical position, was constructed. The guide consisted of a ball bearing roller, to which the top of the soil probe was attached, mounted inside a vertical track and was positioned above the soil cylinder.

The concentric tube probe design consisted of an outside casing containing an internal compressed gas delivery tube. The internal tube was connected to a pneumatic boring/transporting tip at the bottom end of the probe. At the upper end of the probe, a bored through tee fitting established the concentric geometry and provided an outlet for the transported soil. In operation, the compressed gas exiting the boring tip would loosen the sand, transport it up the annulus between the concentric tubes, and blow it out the branch of the tee fitting.

The casing was constructed of a 12.7 mm outside diameter rigid aluminum tubing, 2.15 m long, with a 10.9 mm inside diameter. One centimeter gradations were marked on the casing to monitor probe penetration. The internal gas delivery tube was soft aluminum having a 3.2 mm outside diameter and a 1.9 mm inside diameter. Connected to the gas delivery tube was the boring tip, which was fit into the inside of the casing tube. Sand samples, exited the probe through the tee fitting branch but were not retained or captured by any collection device. The outside surface of the probe was coated with a teflon spray and the boring tip was filed to a sharp edge in an effort to reduce penetration resistance.

A cylinder of compressed gas provided the energy, in the form of pressurized gas pulses, for soil boring and fluidization. The cylinder pressure was monitored with a gauge, accurate to 34 kPa, while the working gas pressure was controlled with a regulator. Positioned between the regulator and the probe was an electrically actuated solenoid valve which was used to modulate the gas pulse. An electronic controller, connected to the solenoid valve allowed modulation of gas pulse duration and frequency.

Test Procedure

Once the test rig was constructed, the silica sand was placed in the plexiglass cylinder and consolidated by operating the pneumatic vibrator. Weight and height of sand in the column was monitored, and the bulk density calculated, during the consolidation process. Once the bulk density values achieved a constant value, the sand was considered adequately consolidated and the engineering parameter tests were initiated.

The purpose of the engineering parameter tests was to optimize probe penetration efficiency (minimize gas usage). The probe boring depth, boring time and gas usage were evaluated while maintaining constant bulk sand density and probe weight. The original test matrix (shown in Table 1, included three working gas pressures, pulse durations and pulse frequencies which were to be evaluated in a full factorial test matrix. Once the tests commenced, it became obvious that the lower working pressure and lower pulse frequency would not allow sufficient gas delivery to effect significant probe penetration. As a result, the test matrix was revised to include only the two higher working gas pressures and pulse frequencies. Also, to evaluate repeatability, multiple tests were conducted at each condition.

Before each test, the sand was compacted to the bulk density achieved during the initial compaction efforts, i.e. the same column weight and fill height. The column weight and fill height were recorded. The probe was connected to the guide and compressed gas line, the boring tip was set on the sand and the system weight was again recorded.

Table 1: Test Matrix

Test #	Pressure (kPa)	Frequency (pulse/min)	Duration (sec)
1	1034	40	0.2
2			0.3
3			0.4
4		30	0.2
5			0.3
6			0.4
7		20	0.2
8			0.3
9			0.4
10	1379	40	0.2
11			0.3
12			0.4
13		30	0.2
14			0.3
15	1379	30	0.4
16		20	0.2
17			0.3
18			0.4
19	1724	40	0.2
20			0.3
21			0.4
22		30	0.2
23			0.3
24			0.4
25		20	0.2
26			0.3
27			0.4

The desired working gas pressure, pulse frequency and pulse duration were set and the initial compressed gas cylinder pressure was recorded. Tests were initiated by activating the pulse controller and recording the starting time. During each test, the time to penetrate to the depths of 0.5, 1.0, 1.5, and 2.0 meters was recorded. Each test was terminated at 30 minutes or full probe penetration, which ever came first.

At the completion of each test, the compressed gas cylinder pressure, working gas pressure, and the total system weight (with the probe still at full penetration) were recorded. The probe was removed and the weight of the system was again recorded.

Initial probe weight was determined from the initial system weights with and without the probe setting on the sand. Final probe weight (at full penetration) was calculated from the final system weights taken with and without the probe inserted. Weight of sand ejected from the system by the probe was determined from the initial and final system weights taken without the probe contribution.

Test Results

The size distribution for the silica sand is shown in Figure 2. The other pertinent sand characteristics are shown in Table 2.

Table 2: Soil Characteristics

ASTM Classification	medium sand
Gradation	uniform
Shape	angular
D_{10} (effective grain size; 10% of particles are finer than)	0.3 mm
D_{50} (50% of particles are finer than)	0.5 mm
Average bulk density	1490 ± 5 kg/m^3
Angle of repose	30°
Cohesion	none

Table 3 contains a condensed summary of the data from the revised parametric test program. Full two meter penetration was achieved for each of the test conditions. The average probe mass before penetration was 1.18 ± 0.09 kg while the average probe mass at full penetration was 1.16 $\pm$ 0.12 kg. A minimum of two repeat tests were conducted at each test condition for which the time and mass of gas required to achieve penetration of two meters are shown as well as the amount of sand removed through the probe. The results for each repeat test at a given condition are separated by a backslash and are listed from left to right in the order that the tests were conducted. Three tests were conducted at each condition for the lower working gas pressure while two tests were conducted at the higher pressure, Each set of repeat tests which span all of the frequency and duration conditions for a specified working gas pressure is referred to as a test series.

The repeat tests which comprise test series 1 and 2 were conducted back-to-back for each set of conditions. First the lower gas pressure, lower pulse frequency tests were conducted in the order of lowest to highest pulse duration. The pulse frequency was adjusted to the higher value and the tests were conducted in the same pulse duration order. Data for test series 1 and 2 at the

Table 3: Summary of Results

Test #	Working Pressure (kPa)	Pulse Freq. (#/min)	Pulse Dur. (sec)	Total Time (sec)	Gas Usage (kg)	Sand Removed (kg)
1	1379	40	0.2	4.5 / 11.4 / 4.4	.31 / .85 / .35	.83 / .60 / .67
2			0.3	4.1 / 4.5 / 5.5	.29 / .38 / .45	.63 / .86 / 1.12
3			0.4	4.1 / 6.4 / 4.2	.31 / .50 / .33	.70 / .64 / 1.92
4		30	0.2	3.4 / 3.3 / 10.4	.17 / .17 / .59	.56 / .52 / 1.44
5			0.3	3.3 / 3.3 / 10.4	.21 / .17 / .60	.53 / .57 / 1.87
6			0.4	2.5 / 3.3 / 15.0	.16 / .21 / .91	.50 / .55 / 3.30
7	1724	40	0.2	4.1 / 4.0	.35 / .28	.79 / .73
8			0.3	3.5 / 3.4	.31 / .31	.77 / .69
9			0.4	3.4 / 4.0	.33 / .38	.72 / .75
10		30	0.2	2.4 / 2.5	.17 / .16	.54 / .59
11			0.3	2.5 / 2.1	.19 / .14	.56 / .61
12			0.4	3.5 / 3.0	.28 / .21	.93 / .60

higher working gas pressure were then collected in the same pulse frequency and duration order.

To assess if the results were somehow affected by the sequencing of test runs, a third test series was conducted at the lower working gas pressure. In this test series the sequencing of the tests (pulse frequency, pulse duration) was as follows: (40,0.2), (30,0.2), (30,0.3), (40,0.3), (40,0.4), (30,0.4).

Average probe penetration time as a function of pulse duration is displayed for a working pressure of 1379 kPa in Figure 3, and for a working pressure of 1724 kPa in Figure 4. Similarly, average gas usage as a function of pulse duration is displayed for a working pressure of 1379 kPa in Figure 5, and for a working pressure of 1724 kPa in Figure 6.

DISCUSSION OF RESULTS

Sand penetration to a depth of 2 meters was achieved under all conditions tested. Full penetration times were lowest for the higher working pressure, lower pulse frequency condition. However gas usage at this condition was no better than that produced at the lower working gas pressure, lower pulse frequency condition. Looking at only test series 1 and 2, it appears that the lowest penetration times and gas usage were obtained at the lower pulse frequency, for both working gas pressures. While the reason for this is unclear, the amount of sand removed at the higher pulse frequencies was greater, indicating that additional mining around the tip of the probe was occurring

Results for test series 3 (conducted at the lower working gas pressure only) show increased penetration times and gas usage, particularly at the lower pulse frequency condition. Efforts to repeat the previous tests yielded substantially higher penetration times and gas usage. Thinking that the problem may be associated with differential compaction in the column, the sand was removed and replaced in a fashion consistent with previous column conditions. Still the probe performance was not on par with earlier test results. While the probe did not visibly show significant wear, it was possible that increased penetration resistance associated with frictional wear was responsible for these results. The probe was refurbished by recoating the outside surface with teflon spray and refiling the tip to a sharp edge. Tests conducted subsequent to the probe maintenance produced results similar to those of the earlier test series.

The design and orientation of the probe tip was critical to boring efficiency. Several different designs and modifications were tried during preliminary tests to determine an effective distribution of gas flowrate and velocity. The shape of the probe tip was also critical. Optimization of the probe tip was outside the scope of the present work but will require further attention in future research.

To help understand the research data, a preliminary effort was made to describe the mechanism involved during soil penetration. If the probe was simply being pushed into the silica sand, soil mechanic calculations relating to pile resistance in cohesionless soils could be used to estimate the normal force required for a specified penetration depth. These formulas divide the total pile force into resistance due to skin friction (which is a function of pile surface area and smoothness) and point resistance (which is a function of pile cross sectional area). Both resistances are also dependant on the soil friction angle and bulk density. If it is assumed that the working gas exiting the probe removes effectively only the soil from the tip proximity, then the point resistance would go to zero and the skin friction would be the total resistance to penetration. This reasoning indicates the importance of a smooth, slick probe skin which may warrant an investigation of potential surface coatings. Calculations based on this premise yield a force of 431 N required to achieve a 2 meter probe penetration. However, with a total probe force of approximately 13 N, full penetration was achieved for each condition. Hence, soil mechanic calculations examined in this preliminary effort do not fully explain probe penetration.

It appeared that the penetration resistance was inversely related to the soil compaction. Penetration times decreased after the sand was consolidated by using the pneumatic vibrator. It is possible that as sand compaction increases, interlocking between the angular particles also increases. As the sand is loosened around the tip allowing the probe to drop into the fluidized cavity, the integrity of the bore hole created is at least partially maintained by particle interlocking. As a result, the sand does not completely collapse against the sides of the probe, therefore the horizontal soil stress and predicted penetration resistance are not realized.

During preliminary tests, penetration times into the sand, at a given set of conditions, varied considerably. Usually the probe would reach the two meter depth but penetration time and sand flowrate exiting the probe would not be consistent. To determine whether oversized particles in the sand were causing this variability, the sand was removed from the column and the plus 1 mm particles extracted. After replacing and consolidating the classified sand, 2 meter penetration times became significantly more consistent. The probe is, however, able to handle a larger particle size distribution than that employed and penetration times can be minimized with an optimized boring tip design.

After all test series were completed, the sand was drained from the column down to a depth of 150 cm. A 10 cm layer of crushed oil shale with the same size as the sand, was placed at that depth and the column was refilled. A single penetration test was conducted at conditions typical of those previously described and a visual evaluation of the sample exiting the probe was conducted. At the 150 cm depth, the probe sample appeared to be all shale and continued to be all shale through the 10 cm seam thickness. These qualitative results indicate that the probe is delivering samples to the surface consistent with the penetration depth.

All tests reported were conducted with N_2 working gas which has a molecular weight of 28 and a dynamic viscosity of 0.018 cP. In a Martian environment, the working gas may be CO_2 which has a molecular weight of 44 and a dynamic viscosity of 0.012 cP. To quantify the effect using a different working gas, a short series of tests were conducted using N_2 and CO_2 at a pulse frequency of 40 pulses/min and duration of 0.2 seconds with a working gas pressure of 1170 kPa. Tests with the CO_2 working gas took twice as long for full penetration but used only 50% of the gas required for the N_2 tests. The higher penetration times associated with the CO_2 gas can be related to it's lower viscosity which will result in a lower particle drag force. The lower CO_2 gas usage is a result of it's higher molecular weight which, for a given pressure drop, is directly related to gas volume and therefore gas velocity.

It is envisioned that the working gas pressure required for an actual Martian sampler would be determined based on final equipment designs. Our test rig was not optimized for minimal pressure drop and therefore operation at lower gas pressures was not feasible. Of practical concern is the gas velocity at the boring tip and within the probe casing. Taking the total mass of gas used and dividing by the number of pulses yields an average gas use per pulse. Dividing this value by the pulse duration gives the mass of gas used per second. Assuming that all of the gas exiting the boring tip eventually exits the soil through the casing, the average gas velocity (within the probe casing) generated by each pulse is 1.7 m/sec for a working pressure of 1379 kPa. Because of the lower gravity on Mars (resulting in lower particle weights), it may be possible to reduce the transport gas velocity and hence the total gas usage.

Future Research Requirements

While the results of the research described in this report show the feasibility of pneumatic soil sampling, they also point to areas which require closer scrutiny. For example, the effects of soil consolidation and particle size on probe performance should be evaluated. Several aspects of probe design should be investigated including boring tip geometry, casing friction reduction and flexible casing design. With all soil and probe evaluations the question of gas usage must be addressed.

Once these basic research areas have been adequately studied, a probe development program can begin. This work would include design and construction of a pneumatic soil sampler prototype and would entail development of novel techniques for probe storage and sample collection as well as gas compression and storage. A concept drawing of a pneumatic retractable soil sampler is shown in Figure 7. The sampler would mount on the rover and modulated compressed gas would be provided from the rover platform to the probe reel. The collapsible probe casing and flexible compressed gas line would be spooled on the probe reel prior to boring initiation. When boring begins, the pulsed compressed gas will commence and the probe will be unspooled from the reel. A probe drive/guide will be used to maintain constant penetration force. Sample ejected from the casing will be deflected from the sample collector, by purging the analyzer with a simultaneous pulse of compressed gas, until desired probe penetration is achieved. The sample will then be educted into the analyzer for desired evaluation. After the sample has been collected for evaluation, the probe will be extracted by reversing direction on the probe drive. The probe will be respooled on the reel and the rover could be positioned for another boring.

SUMMARY

The pneumatic soil sampler concept was successfully demonstrated by penetrating a Martial simulant soil to a depth of 2 meters. Working gas pressure, composition and pulsing were evaluated with the objective of minimizing gas usage. Also, the probe penetration force was investigated with the objective of minimizing probe weight. Gas usage and probe penetration force, while not yet optimized, are within the range which make the soil sampler concept feasible. While the tests described in this report did not answer all the questions and address all the variables associated with pneumatic soil sampling, valuable data experience and knowledge were gained which can be used to further develop the concept.

REFERENCES CITED

1. Stoker, C.R., Gooding, J.L., Roush, T., Banin, A., Burt, D., Clark, B.C., Flynn, G., Gwynne, O., 1993, "The Physical and Chemical Properties and Resource Potential of Martian Surface Soils", *Resources of Near-Earth Space*, ed. J. Lewis, M.S. Matthews, M.L. Guerrieri, The University of Arizona Press, pp. 659-707.

Figure 1: Soil Sampler Test Apparatus

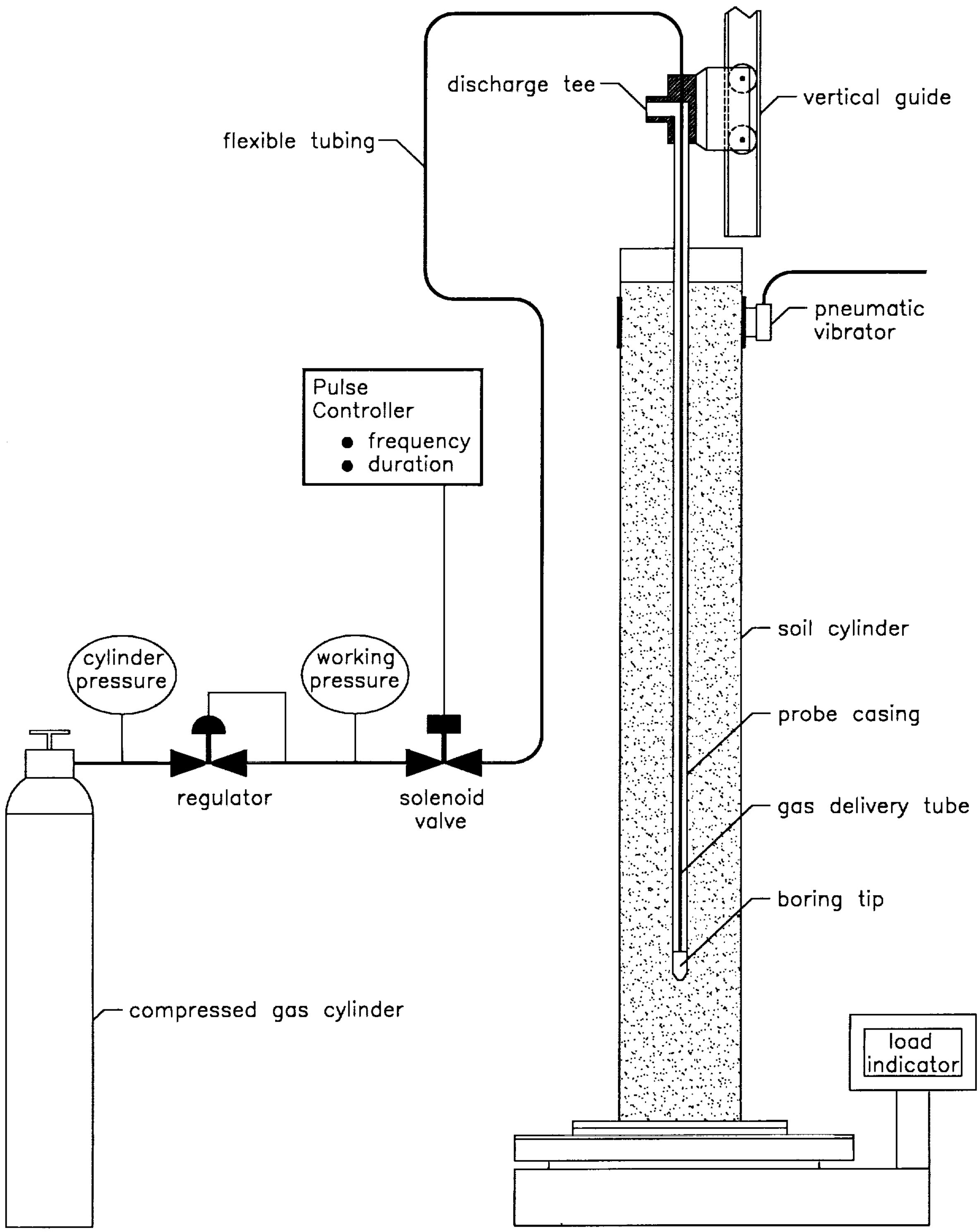


Figure 2: Size Distribution of Play Sand

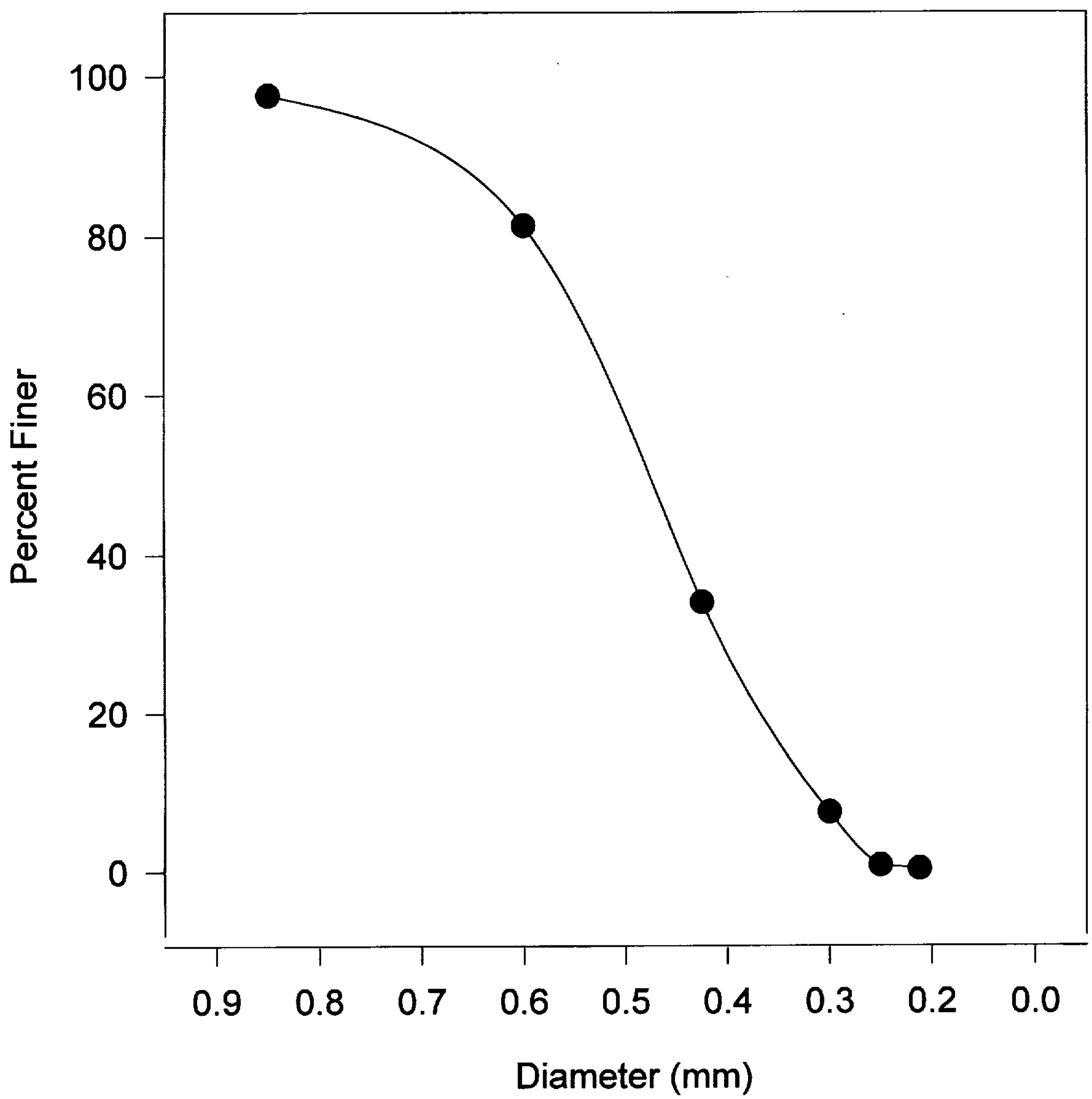
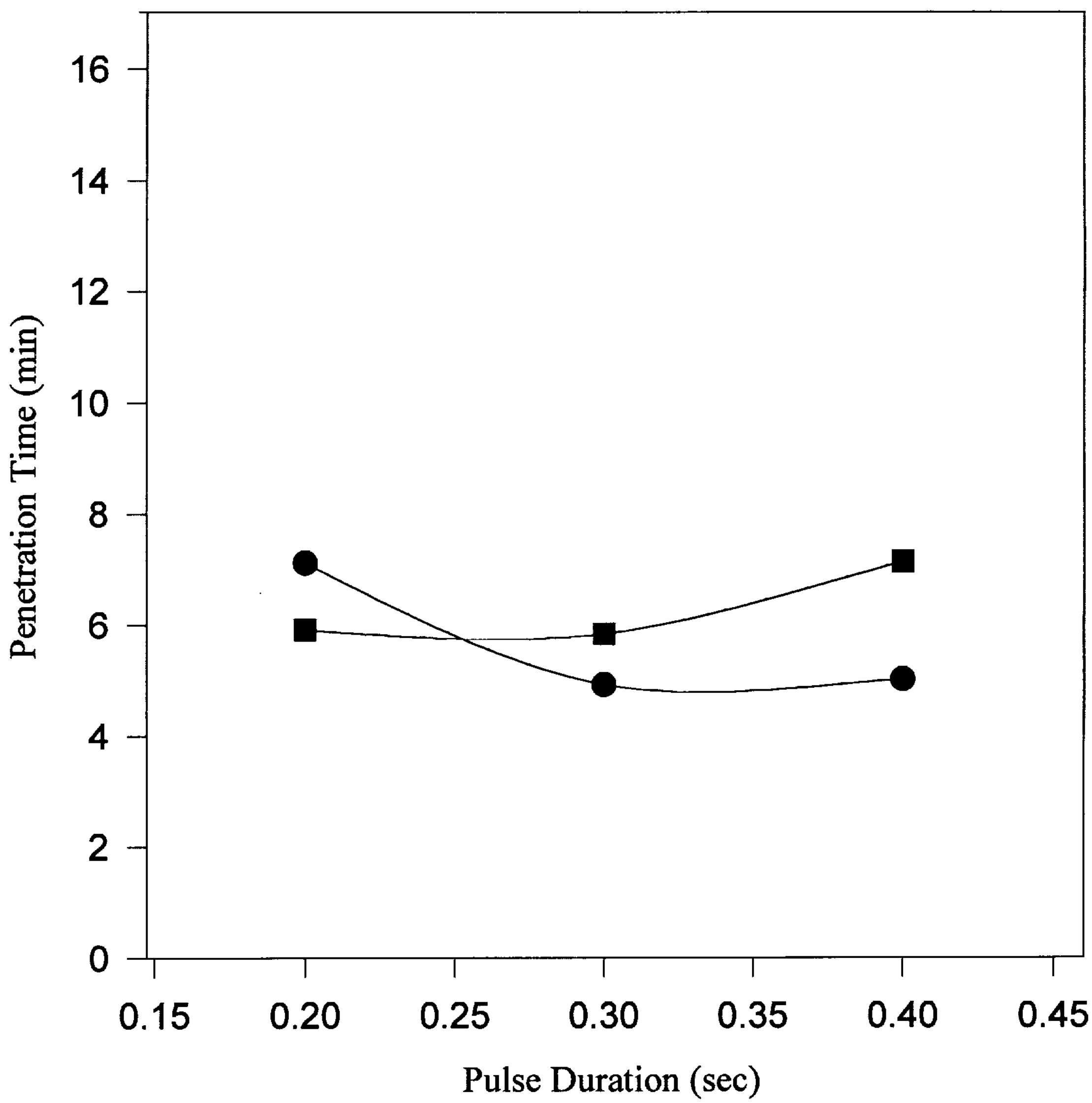


Figure 3: Time to Penetrate 2m vs Pulse Duration
(working pressure = 1379 kPa)



■ frequency = 30 pulses\min

● frequency = 40 pulses/min

Figure 4: Time to Penetrate 2m vs Pulse Duration

(working pressure = 1724 kPa)

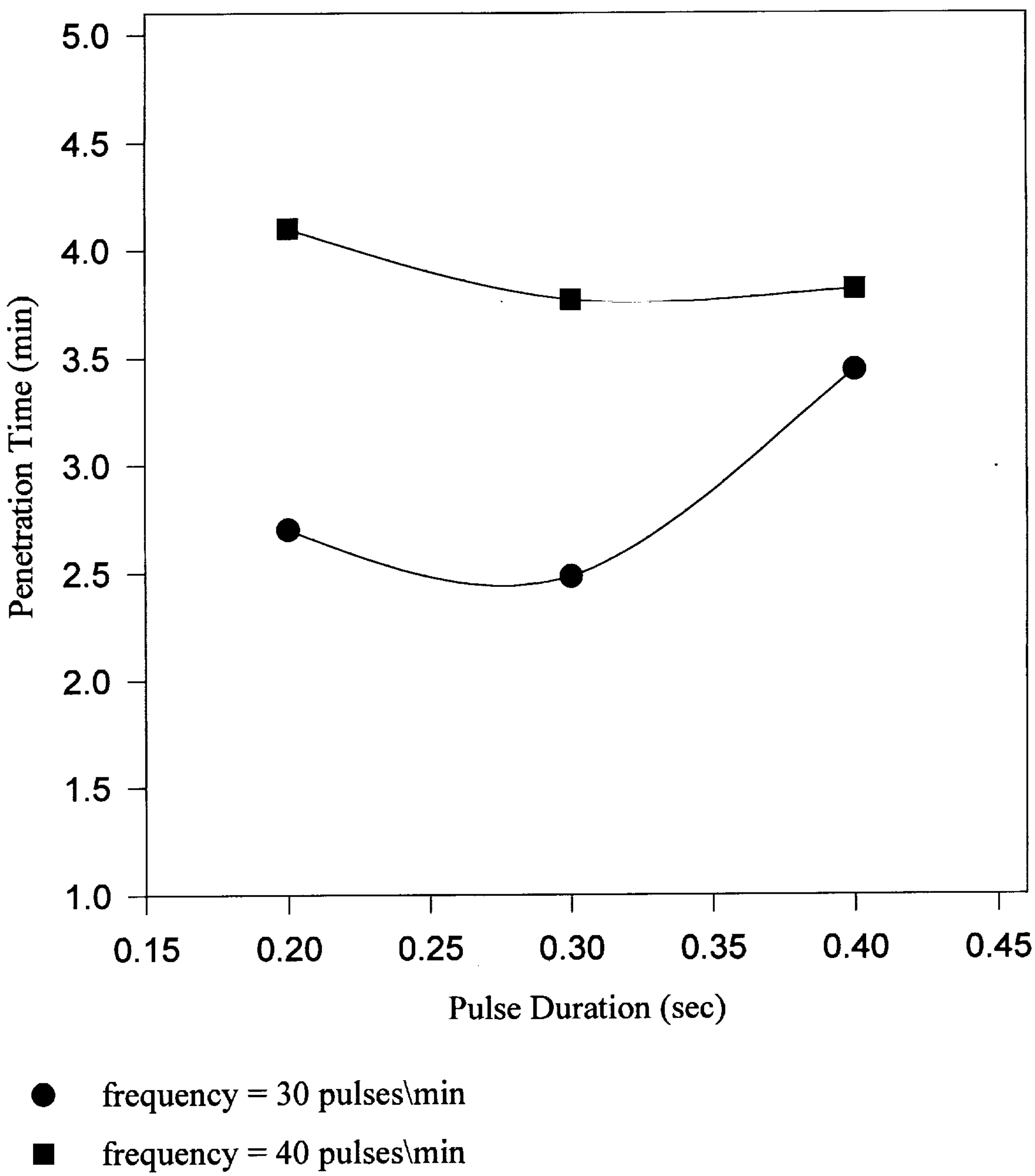


Figure 5: Gas Usage vs Pulse Duration

(working pressure = 1379 kPa)

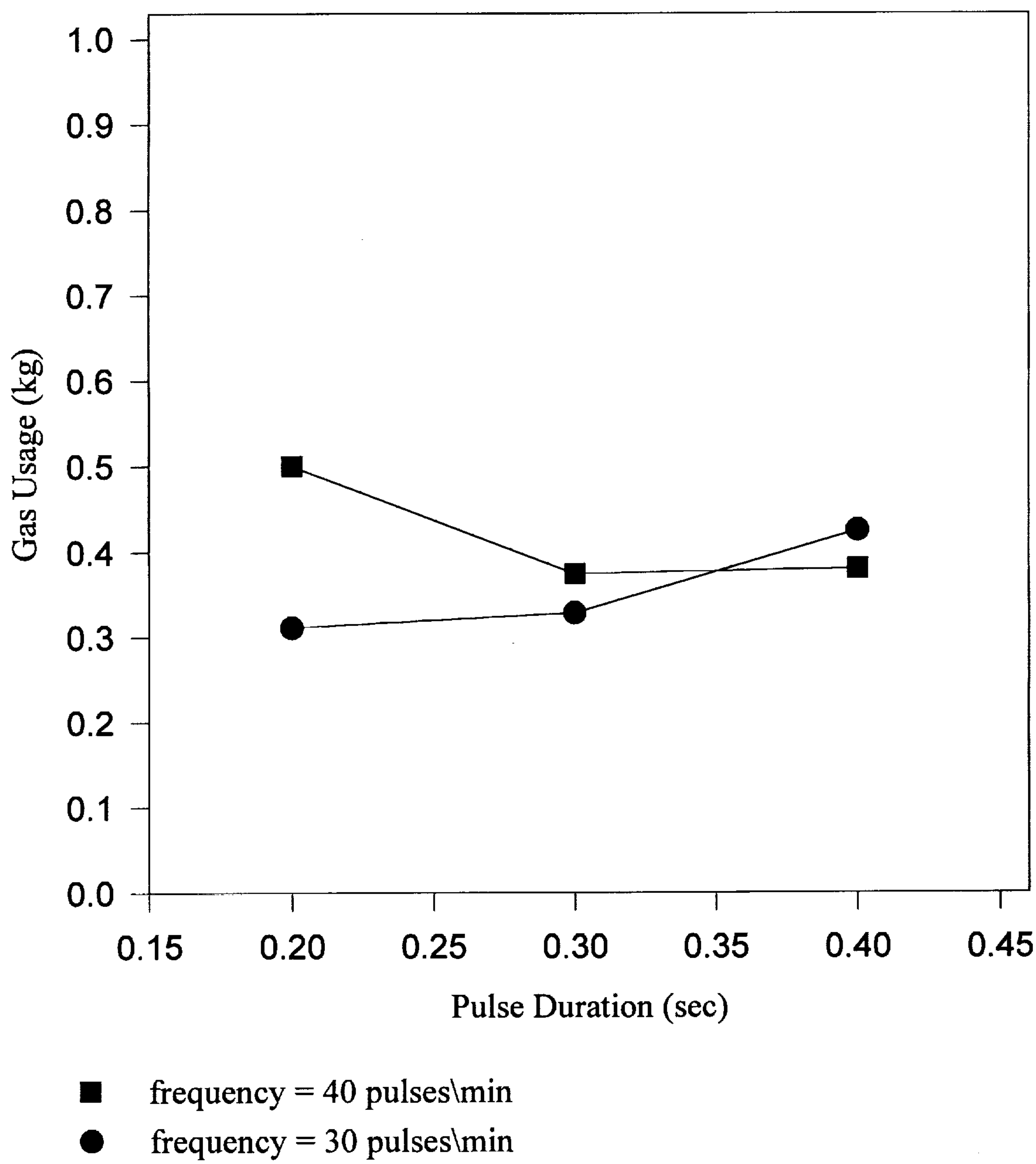


Figure 6: Gas Usage vs Pulse Duration
(working pressure = 1724 kPa)

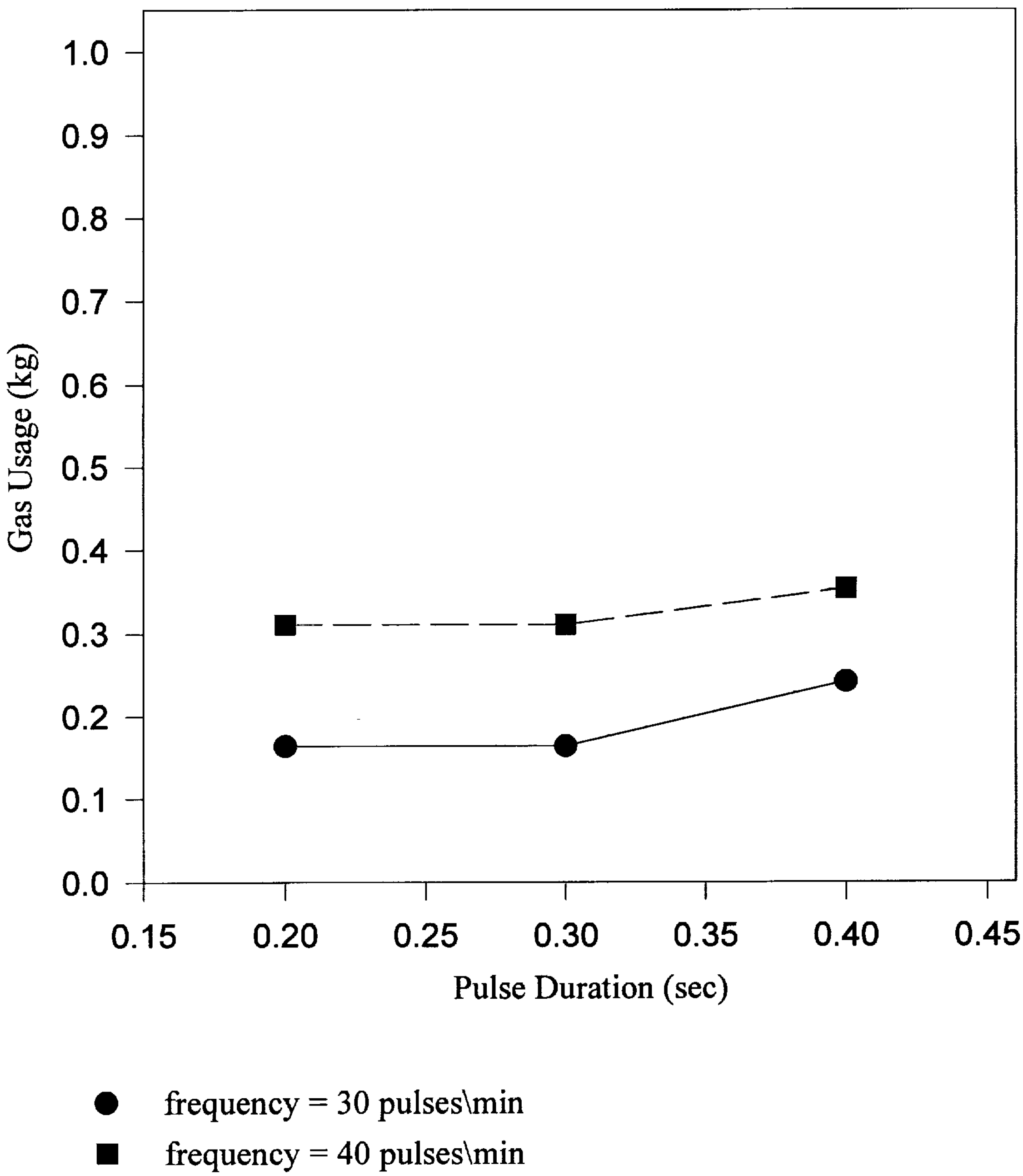


FIGURE 7: CONCEPT FOR RETRACTABLE SOIL SAMPLER